NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

November 1941 as
Advance Restricted Report

INVESTIGATION OF PERFORMANCE OF 9-CYLINDER ENGINE USING LARGE VALVE OVERLAP AND ECLIPSE FUEL-INJECTION SYSTEM

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INTRODUCTION

Single-cylinder tests made with several different engines over a period of years have shown that a large overlap between the time of inlet valve opening and exhaust valve closing results in a considerable increase in the maximum power obtainable from a supercharged engine and reduces the cylinder temperatures at a given power output. (See references 1, 2, and 3.) However, large valve overlap requires the use of fuel injection into the cylinder in order to prevent fuel from being wasted in case some of the intake air passes directly out through the exhaust valve during the overlap period. Furthermore, idling of the engine equipped with valve overlap is almost impossible unless special provisions are made to improve it.

In order to learn something of the practical possibilities of using large valve overlap the Bureau of Aeronautics loaned to the Committee a 9-cylinder radial engine equipped with a fuel-injection system. A special cam ring giving 130° of valve overlap was obtained for this engine. This report discusses the results of tests made with this engine to determine the power output and to investigate means for improving the idling, together with idling tests made on a single-cylinder engine.

EQUIPMENT

The engine used for these tests was a 9-cylinder Pratt & Whitney "Wasp" R-1340-12. It had a compression ratio of 6 to 1, a blower drive ratio of 10 to 1, and was rated at 550 horsepower at 2100 rpm at sea level. It was equipped with an Eclipse fuel-injection system.

The fuel-injection pump was an Eclipse model M-3475X. It was mounted on the rear of the engine and driven through gearing from the starter shaft. The pump consists of nine lapped plungers arranged in a circle with their axes parallel. They are operated through a constant stroke by means of a cam. The fuel quantity is controlled by varying the start of injection by moving axially nine hardened steel spools which ride on small-diameter extensions of the plungers. These plunger extensions project through the main body of the pump into a low-pressure fuel chamber. By-pass ports in the plunger extensions are covered by the spools at the point in the plunger travel at which it is desired to have the injection start. An automatic mixture-control device is made integral with the pump. This device is supposed to regulate the air throttle according to the pump throttle position and the manifold pressure and temperature. However, this device was disconnected for all tests and the fuel-air ratio was regulated by adjusting the pump and air throttles separately.

The fuel-injection valves are screwed into special holes in the cylinder heads as shown in figure 1. At a fuel pressure of 450 pounds per square inch the spring loaded valve stem opens inwardly toward the combustion chamber to inject the fuel in a cone-shaped spray of approximately 28° included angle. The injection was timed to start at about 40° after top center on the suction stroke for full-load fuel quantity. The full-throttle injection period is approximately 80 crankshaft degrees.

The engine cylinders and pistons had been modified as shown in figure 1. The intake valve is shorter than standard and is partially shrouded by the ledge which has been added in the cylinder head. The top of the piston is grooved in eccentric circles for the purpose of reflecting the fuel spray and improving the mixing of the fuel and air.

Single-cylinder tests had been made with the same type of cylinder piston, and injection equipment and with cams giving normal timing and valve overlaps of 120° and 140°. As a result of the information obtained in these tests, 130° of valve overlap was chosen as the timing for a special cam ring for the R-1340-12 engine.

The designed valve timing with the standard cam and with the overlap cam is given in table I. The actual timing was within a few degrees of these values. It will be noted that the overlap timing changed only the intake opening and exhause closing events.

Army Air Corps 100-octane gasoline was used in all tests. One-half of 1 percent of lubricating oil was added to the gasoline to insure some lubrication of the injection pump plungers.

The engine was first mounted upon an outdoor torque stand. This stand was actually a model mounting frame from the 20-foot propeller-research tunnel. A flight propeller was used to absorb the engine power and to supply cooling air. A torque balance served to give a rough check of the power output, but accurate power measurements with this equipment were not possible because of the variable effect of the wind. This equipment was used to make preliminary tests of the engine and injection system and to determine the effect of a system of individual air throttles for each cylinder which was designed to improve the idling of the engine when using valve overlap.

A test bench set-up for the fuel-injection pump and injection valves was used to facilitate checking and adjusting the fuel quantity delivered by each of the pump cylinders.

To obtain data on the engine power with the normal and the overlap cams the engine was mounted on a dynamometer stand of the Air Corps Matériel Division at Wright Field. In this set-up cooling air was supplied by a blower and the engine power was absorbed by an electric dynamometer and a water brake. Additional boost pressure was obtained for some runs by connecting the air intake to the cooling air system of an adjacent test stand.

A single-cylinder test engine having the same type cylinder and piston as the 9-cylinder radial engine was used for idling tests with special hydraulically controlled valve tappets which reduced the amount of valve overlap when idling.

TEST RESULTS AND DISCUSSION

Dynamometer Tests

The dynamometer tests were carried out at speeds of 1500, 1700, 1900, 2100, and 2200 rpm. A range of manifold pressures from 22 to 38 inches of mercury absolute was covered at each speed except where the highest value could not be reached. The lower pressures were obtained by partly closing the air throttle valve which replaced the carburetor on this engine. When full-throttle manifold pressure was reached the engine was boosted still further by taking air from the cooling air hood of an adjacent test stand. Approximately 2 inches of mercury increase in the intake stack pressure could be obtained in this way.

Friction runs were made over the same range of speeds and manifold pressures as the power runs. The friction runs were made with approximately the same oil in temperature as the power runs and with no cooling air over the engine.

Figures 2 to 6 show the brake and friction mean effective pressures for this engine over the range of speeds and manifold pressures covered. The results with both the standard cam and the overlap cam are shown on the same figures. The data have been corrected to standard air temperature on the assumption that the indicated mean effective pressure varies inversely as the square root of the absolute temperature at the air intake. This assumption is sufficiently accurate for small corrections. No correction has been made for varying atmospheric pressure because this would involve a change in the back pressure acting on the engine. Instead, the absolute dry atmospheric pressure for each set of runs has been shown on the curves. This is the pressure at the engine exhaust.

It is evident that when the intake manifold pressure and exhaust pressure are equal the power using the overlap cam is approximately the same as that with the standard cam. When the manifold pressure is increased the valve overlap engine shows a rapid improvement in power over the normal engine at first, until a boost of 2 or 3 inches of mercury is reached. At higher boosts the power advantage continues to increase, but the rate of increase drops off, gradually reducing the advantage to a constant figure. As the intake pressure is reduced below the exhaust pressure the power falls off more rapidly with the overlap cam than with the standard cam.

The difference in shape of the curves of brake mean effective pressure versus manifold pressure for the standard and overlap cams is caused by the different amounts of scavenging of the clearance volume. When both the intake and exhaust valves are open for an appreciable time at the top of the stroke, as is the case with 130° of valve overlap, and there is a difference between the intake and exhoust pressures, there will be a flow of air in one direction or the other. When the intake pressure is higher than the exhaust pressure there is a tendency for fresh air to flow into the cylinder, forcing the spent gas out past the exhaust valve. As the pressure difference is increased a larger amount of exhaust gas is replaced with fresh charge. However, with a pressure difference of perhaps 3 to 5 inches of mercury most of the exhaust gas is forced out, and at higher pressure differences fresh air flows out the exhaust port and is wasted. If the pressure diference is increased to a point where no additional exhaust gas is displaced, the slope of the brake mean effective pressure curves for the overlap and standard cams should become practically the same. For the case of the intake throttled below the exhaust pressure the flow through the valves will, of course, be reversed. Some exhaust gas will be drawn into the intake manifold and the amount of fresh charge drawn into the cylinder will be reduced.

Figure 7 shows the percentage change in brake mean effective pressure due to valve overlap, as taken from the curves of figures 2 to 6. The overlap cam shows a rapid improvement of from 11 to 14 percent increase in brake mean effective pressure with the first 3 inches of mercury boost of inlet manifold pressure over exhaust pressure. With increase in boost pressure to about 9 inches of mercury over the exhaust pressure, the maximum reached in these tests, the brake mean effective pressure continues to show an improvement up to 15 to 17 percent. There are some variations in the curves, probably due partly to speed effects and partly to variations in the fairing of the original brake mean effective pressure curves.

The increase in power obtained by using valve overlap is less with this engine than has been obtained on test engines having two inlet and two exhaust valves.

Valve overlap experiments with a number of two-valve and four-valve test engines have indicated that the four-valve construction results in better scavenging of the exhaust gases. (See reference 3.)

The friction mean effective pressure both with the standard cams and with the overlap cams is also shown on figures 2 to 6. The friction is very nearly the same for the two conditions. The slight but consistent difference in favor of the overlap cams may be explained by the fact that the oil in temperatures averaged 5° to 10° F higher during the friction runs with the overlap cams.

Figure 8 shows fuel-consumption loops for two operating conditions with the standard and with the overlap cams. For both conditions the overlap cam shows slightly higher specific fuel consumption both at best economy and at maximum power, although at any given specific fuel consumption more power is obtained when using the valve overlap. The reason for the observed difference in specific fuel consumption is difficult to find. A possible cause might be the increased load on the supercharger due to the larger amount of air used with valve overlap. However, this factor was not sufficient to show up on the friction curves of figures 2 to 6. The fuel consumption throughout these tests was somewhat higher than it should have been because of uneven distribution of fuel among the engine cylinders, as evidenced by differences in the color of the exhausts. The construction of the injection pump made adjustment of the fuel quantity pumped to the different cylinders very difficult, and there was some variation in the relative amounts of fuel pumped to the different cylinders with change in throttle setting.

Idling Tests

An engine using a large amount of valve overlap will not idle properly unless some special provisions are made for idling operation. The reason is that a reduced pressure exists in the intake manifold, and when both valves are open exhaust gas is drawn back into the intake passages. On the following suction stroke some of this exhaust gas is drawn into the cylinder, and when this condition reaches a certain stage it results in uneven running or stalling of the engine. Two ways of overcoming this trouble during idling have been investigated. One reduced the amount of exhaust gas which could be drawn back into the intake system by reducing to a minimum the volume of the intake system which was below atmospheric pressure; the other changed the valve timing to reduce the amount of overlap when idling was desired.

Special throttle valves.- The method of improving the idling with valve overlap which was first tried was the use of separate throttles close to the intake valve of each cylinder. With this arrangement a reduced pressure could exist only in the small space between the intake valve and the throttle, and the amount of exhaust gas which could be drawn from this space into the cylinder on the suction stroke was so small that idling was not affected. This scheme had been found to work well with a single-cylinder engine. (See reference 1.)

The separate throttle arrangement is shown installed on the R-1340-12 engine in figure 9. Figure 10 shows the construction in more detail. A small spacer having a butterfly throttle valve mounted in it was installed between each of the cylinders and its intake pipe. The nine throttles were interconnected by means of a linkage to operate simultaneously. With this arrangement satisfactory idling could be obtained down to 300 rpm with propeller load. However, since there were no stops on the throttles it was easy to stall the engine by closing them completely. A modification was then made by drilling a 0.1285-inch leak hole through each of the butterfly valves. The throttles could then by closed completely and the engine would idle smoothly at 400 rpm. It is probable that with this throttle arrangement exhaust gas is not drawn back even into the small spaces between the intake valves and the throttles, for, during three strokes of the cycle, air can leak past the throttle valves to raise the pressure in these spaces to that in the rest of the intake manifold.

While the separate throttle valves work well to permit idling there are several possible objections to their use. One is the added weight and complication of the separate throttles with their connecting linkage. A second is the throttling of the engine on the pressure side of the supercharger instead of the suction side, which would probably affect the supercharger design and might lead to some sacrifice of supercharger efficiency. However, this objection could be overcome by using the conventional throttle as well, closing the special throttles only for idling. A third possible objection is the difficulty of installing throttles in the intake passages without reducing the volumetric efficiency of the engine.

Controllable valve tappets.- The second means of obtaining good idling operation which was tried was the use of special valve tappets which could be shortened while the engine was running. In this way the tappet clearance was increased and the valve timing changed to reduce the overlap period. This arrangement was tried on the single-cylinder test engine.

The construction of the special valve tappets is shown in figure 11. The "zero-lash" principle for hydraulic valve tappets was used and the design was worked out to include a means for collapsing the tappets to provide a large clearance and reduce the valve lift. Figure 11 shows the tappet assembly in the collapsed position, although the push-rod seat is held up against the push rod by a spring to prevent looseness of the rod. To extend the tappet for normal operation with overlap timing the control valve is turned to allow engine oil under pressure to flow into the tappet. The flow of oil is through the mating holes shown, which register only when the tappet is resting on the circular part of the cam as shown. Oil pressure forces the piston valve down, thus cutting off the oil return passage. Oil then flows up past the ball check valve, forcing the piston away from the valve body and increasing the effective length of the tappet. The tappet is extended in this way to eliminate all clearance, and any oil leakage is replaced with fresh oil each time the tappet comes to the bottom of its stroke. In this way the tappet maintains zero clearance continuously.

When idling operation is desired the control valve is turned to connect the tappet oil line with a drain into the crankcase. This relieves the pressure on the piston valve and the spring forces it upward, opening the oil return passage and permitting the tappet to shorten until the piston rests on the valve body. The engine then operates with a predetermined large clearance which is sufficient to reduce the valve lift to a point where the amount of valve overlap is not objectionable.

The operation of the special hydraulic tappets was checked on the single-cylinder test engine. When oil pressure was applied to them they extended to the normal operating length with no perceptible time lag, and when the drain was opened they collapsed in a period of 2 or 3 seconds. With the engine valve clearance adjusted to 0.095 inch with the tappets collapsed the overlap period was approximately 15 crank degrees and smooth idling was obtained down to 200 rpm.

The special hydraulic tappets furnish a positive method of obtaining good idling operation of an engine using large valve overlap. Perhaps the strongest objection to them is thatmany engines furnish oil to the rocker arms through the valve tappets and hollow push-rod tubes, and the special tappets are not easily adapted to this function.

GENERAL

The data presented have shown the improvement in power which can be obtained by the use of valve overlap. Unpublished data have shown that cylinder temperatures at a given power output are lower for an engine using valve overlap than for one using conventional valve timing. This reduction in temperature is brought about because a given power output is obtained with lower manifold pressures and temperatures and because of the more complete scavenging of the hot exhaust gases. It has also been shown that satisfactory idling can be obtained with an engine using valve overlap provided suitable modifications are incorporated in the engine.

The use of large valve overlap has been prevented largely because of the lack of fuel-injection equipment which was suitable for service use. It may be advisable to point out here the possibility of realizing the advantages of large valve overlap on some engines which use a carburetor. When maximum power is needed only for take-off or emergency conditions, as may be the case for transport or bombardment airplanes, the waste of some fuel during the periods of full-power operation will not be serious. If such engines can be designed to operate with either standard timing or large valve overlap, possibly by the use of a double cam which can be shifted to either operating position at the will of the pilot, more power can be made available for take-off by using the overlap timing, because of the reduction in engine temperatures.

CONCLUSIONS

1. The use of 130 crank degrees of valve overlap resulted in power increases of from 11 to 17 percent at boost pressures from 3 to 9 inches of mercury above the exhaust pressure.

2. Satisfactory idling can be obtained with large valve overlap by using separate air throttle valves close to each cylinder or by using controllable valve tappets which permit increasing the tappet clearances for idling. Any method of using a double set of cams to permit running with either standard or overlap timing will, of course, also permit proper idling.

3. For certain carburetor-equipped engines required to produce maximum power for short periods only the use of large valve overlap may be desirable provided means for operating with either standard or overlap timing can be developed.

4. For the two conditions of speed and manifold pressure tested the overlap cams resulted in about 3 percent higher specific fuel consumptions, accompanied by a power increase of 12 to 14 percent.

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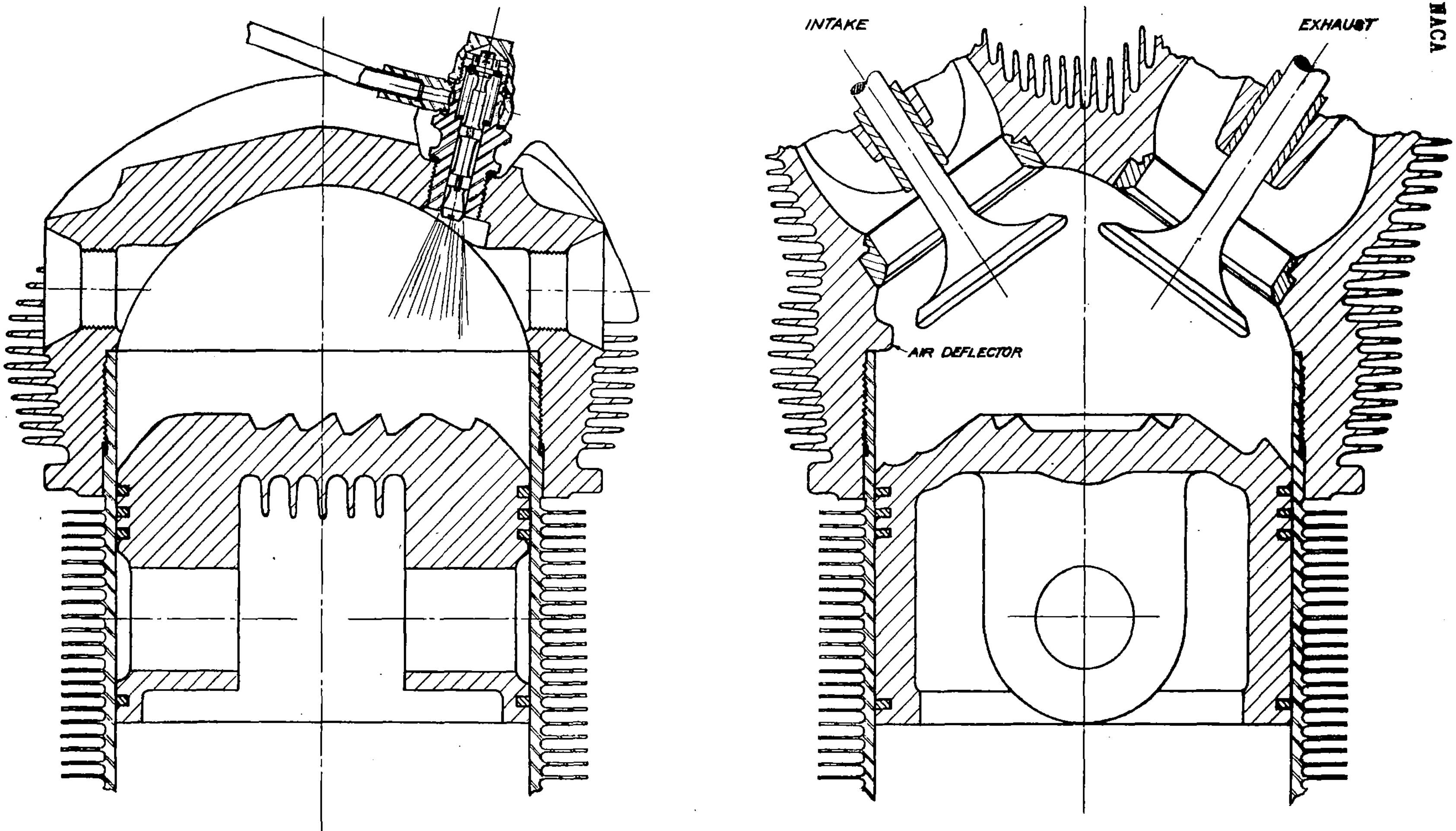
2. Schey, Oscar W., and Young, Alfred W.: The Use of Large Valve Overlap in Scavenging a Supercharged Spark-Ignition Engine Using Fuel Injection. NACA TN No. 406, 1932.

3. Schey, Oscar W.: Performance of Aircraft Spark-Ignition Engines with Fuel Injection. SAE Jour., vol. 46, no. 4, April 1940.

Table I

Valve Timing With Standard and 130° Overlap Cams.

	Standard Timing, deg.	Overlap timing, deg
Intake opens	26 B.T.C.	70 B.T.C.
Intake closes	76 A.B.C.	76 A.B.C.
Exhaust opens	71 B.B.C.	71 B.B.C.
Exhaust closes	31 A.T.C.	60 A.T.C.



SIDE VIEW FRONT VIEW

Figure 1.- Engine cylinder and injection valve.

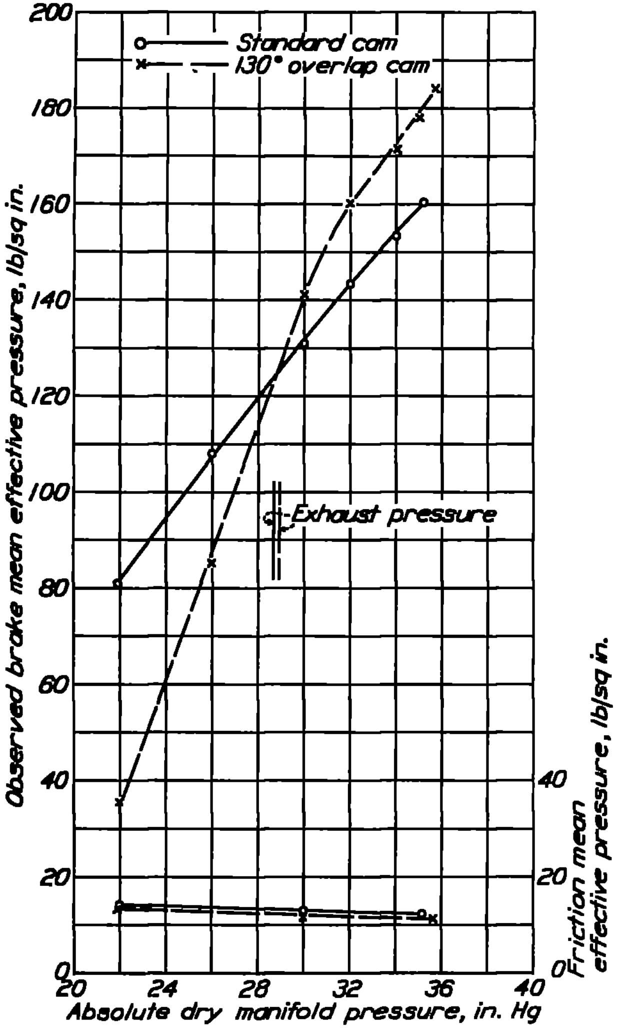


Figure 2.- Brake and friction mean effective pressure at 1500 rpm with standard and 130° overlap cams. R-1340-12 engine.

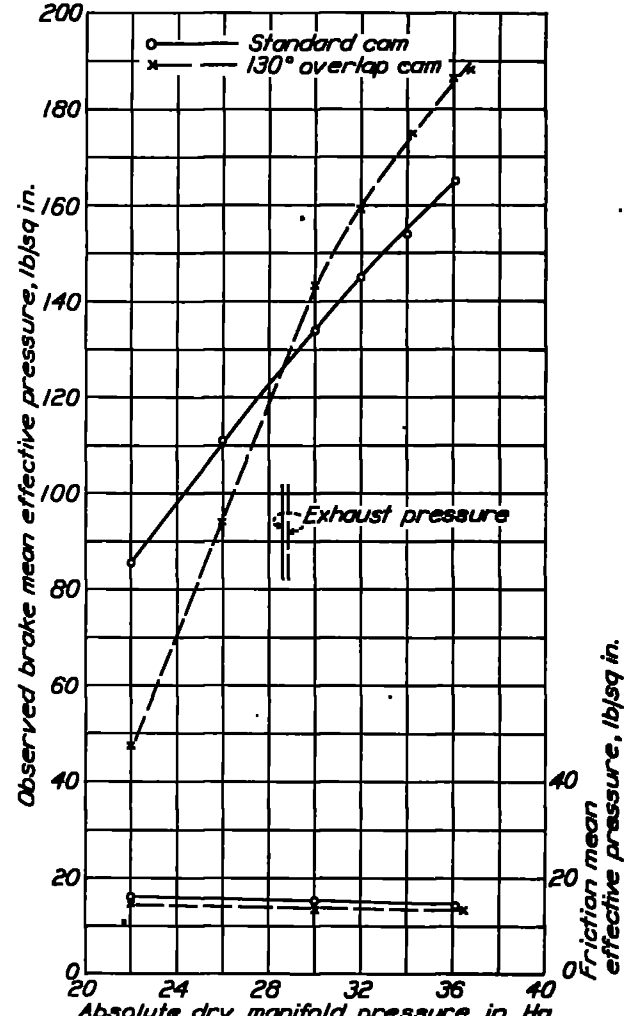


Figure 3.- Brake and friction mean effective pressure at 1700 rpm with standard and 130° overlap cams. R-1340-12 engine.

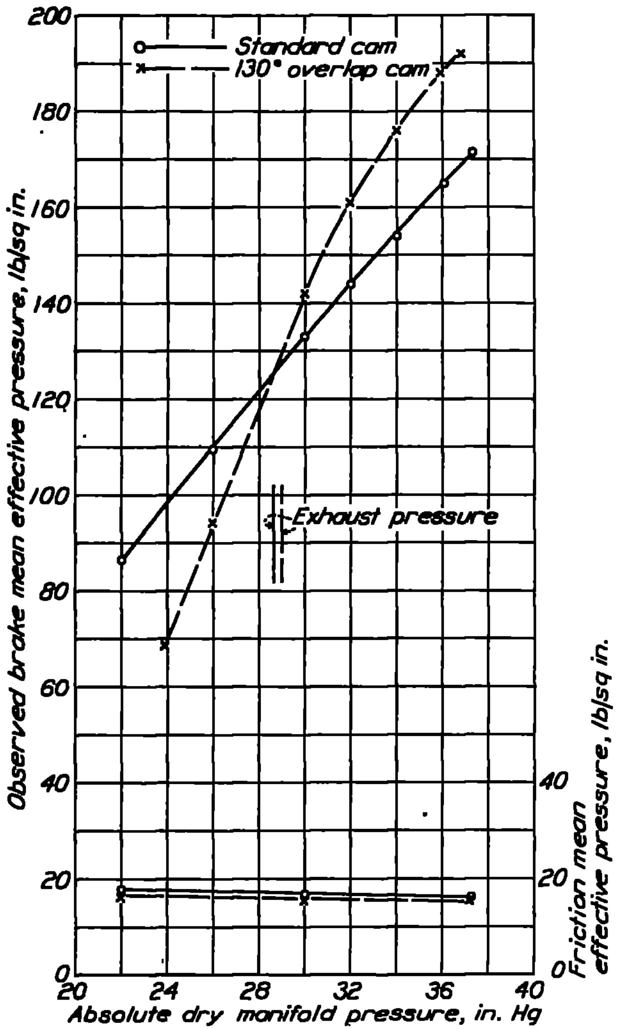


Figure 4.- Brake and friction mean effective pressure at 1900 rpm with standard and 130° overlap cams. R-1340-12 engine.

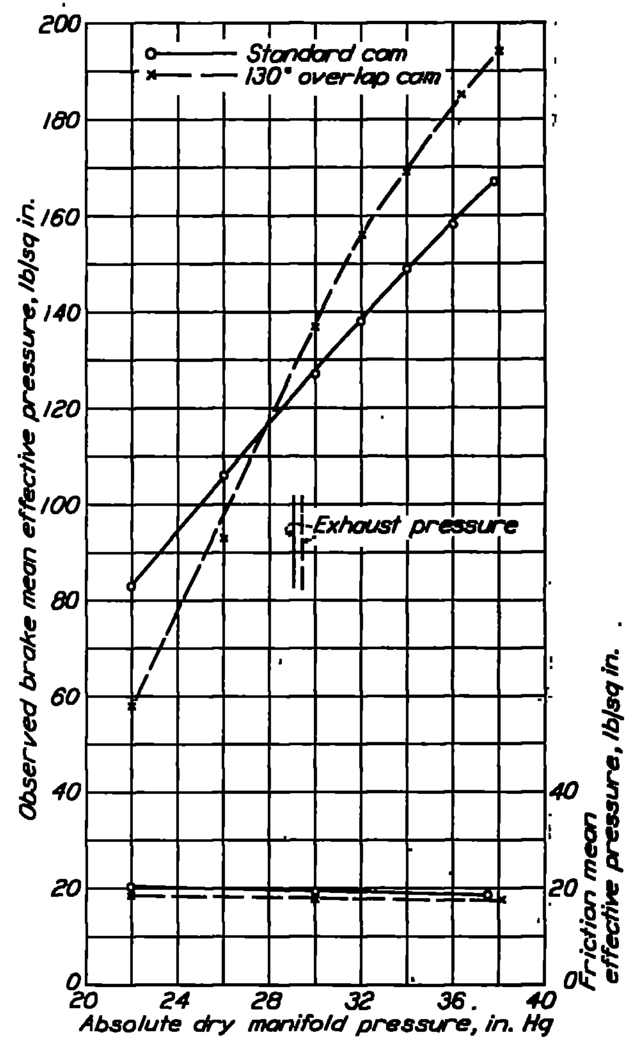


Figure 5.- Brake and friction mean effective pressure at 2100 rpm with standard and 130° overlap cams. R-1340-12 engine.

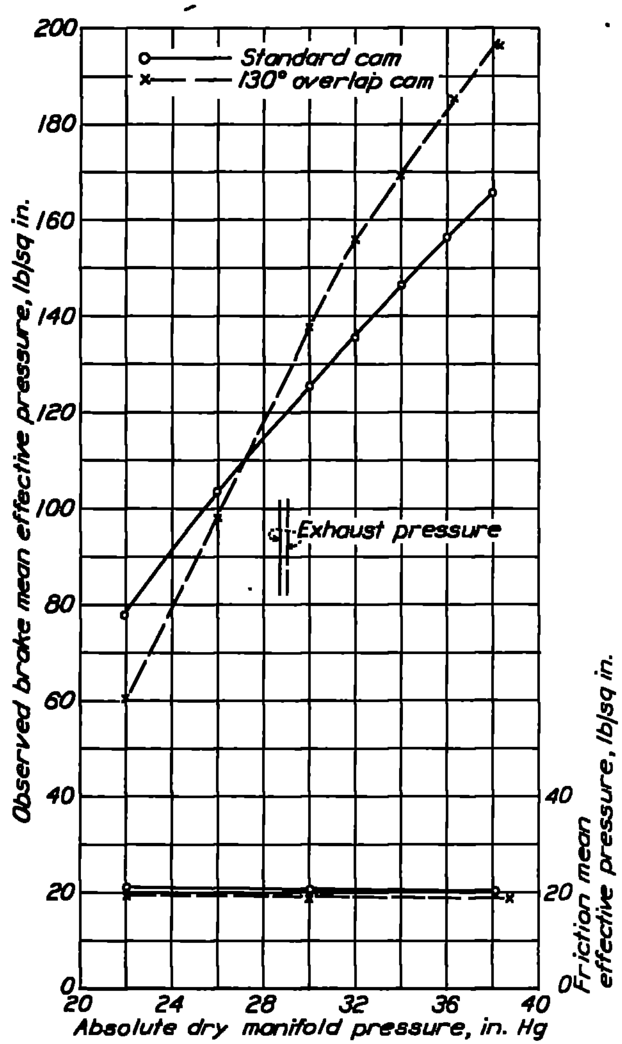


Figure 6.- Brake and friction mean effective pressure at 2200 rpm with standard and 130° overlap cams. R-1340-12 engine.

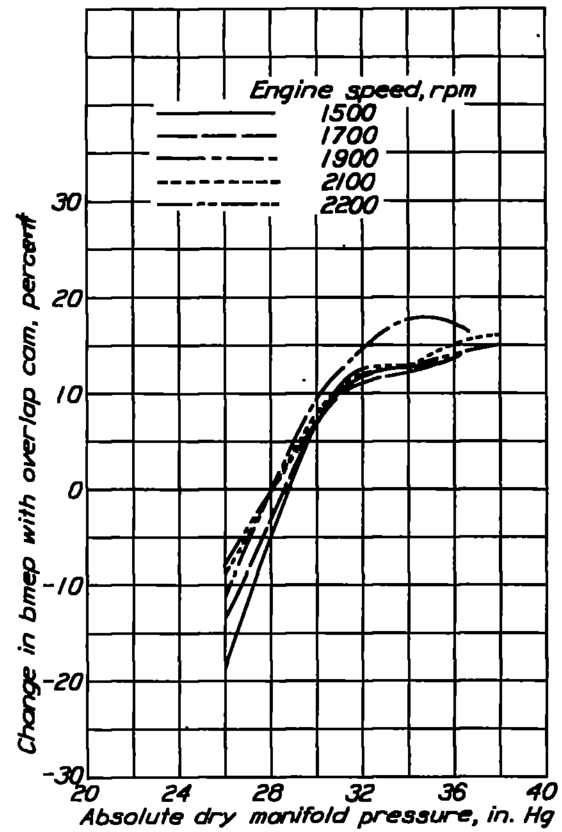


Figure 7.- Percentage change in brake mean effective pressure with 130° overlap cam instead of standard cam. R-1340-12 engine.

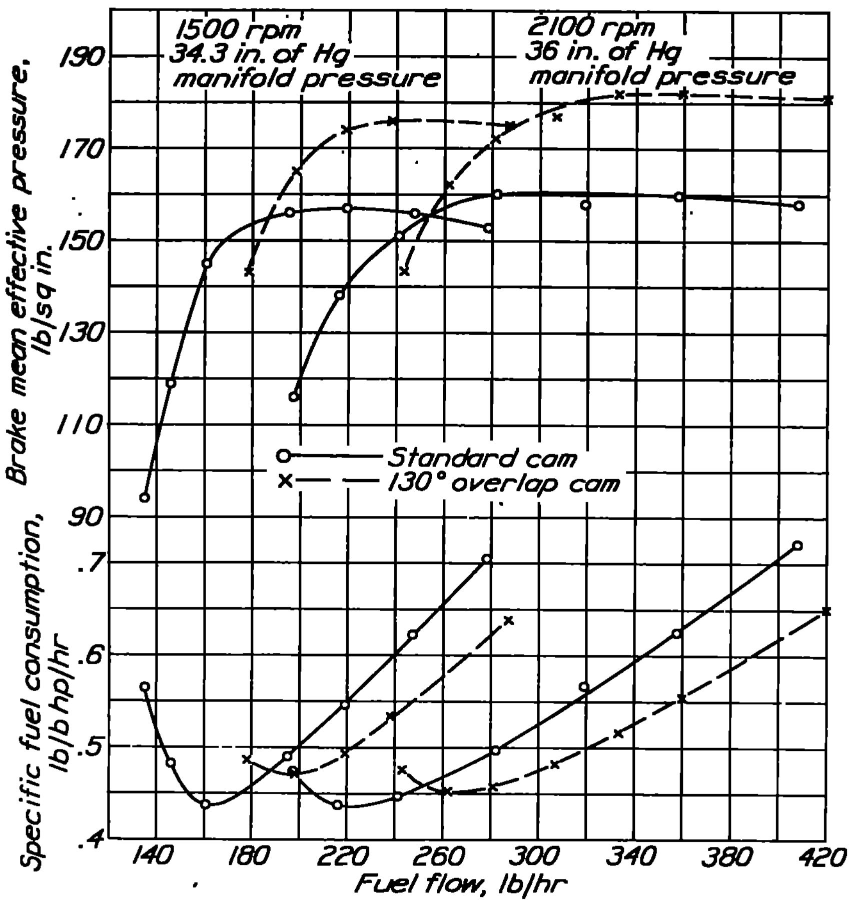


Figure 8.- Brake mean effective pressure and specific fuel consumption with standard cam and with 130° overlap cam for two operating conditions.

Figure 9.- Engine with special air throttles for idling, mounted on outdoor torque stand.

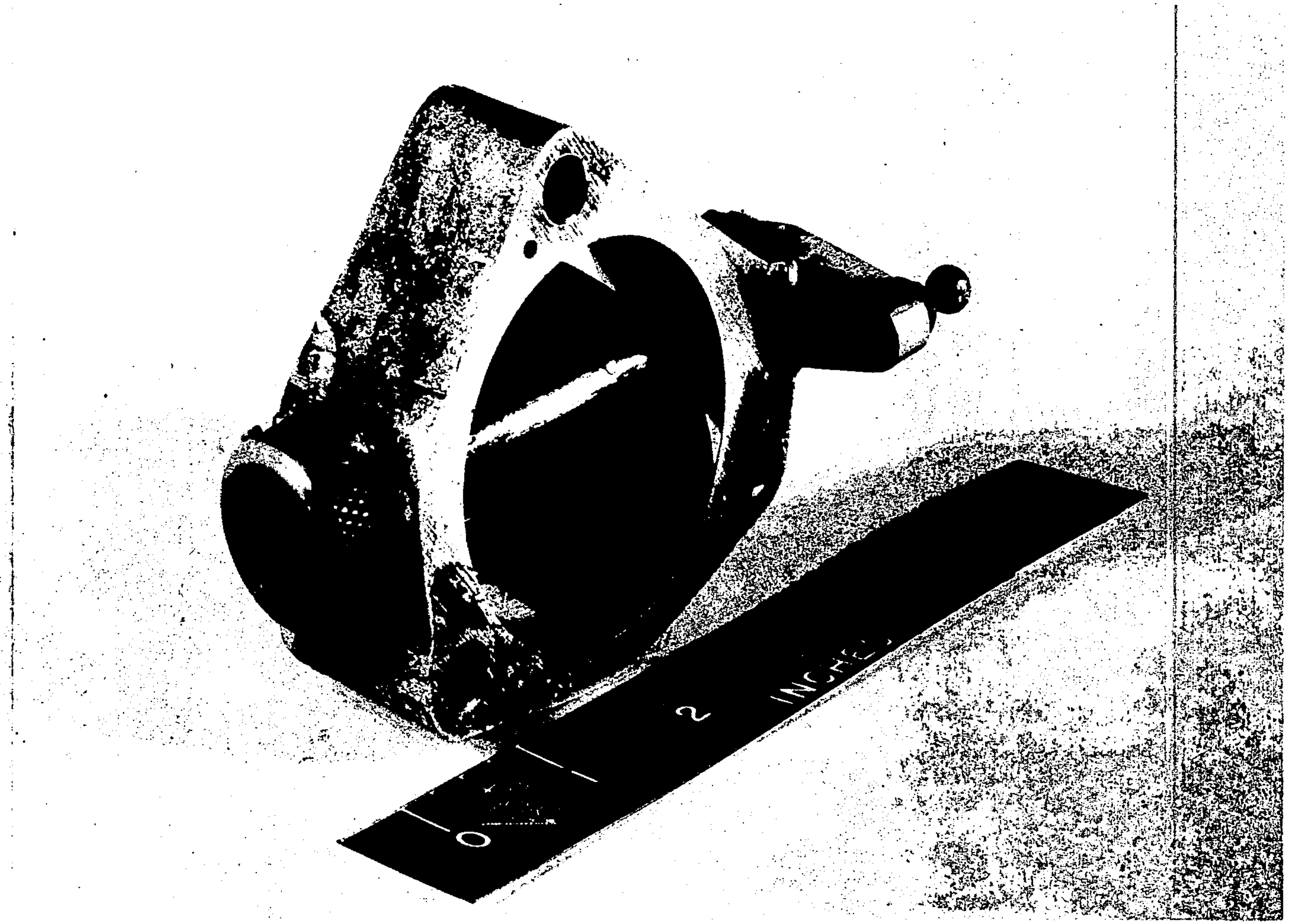


Figure 10.- One of the nine air throttle valves.

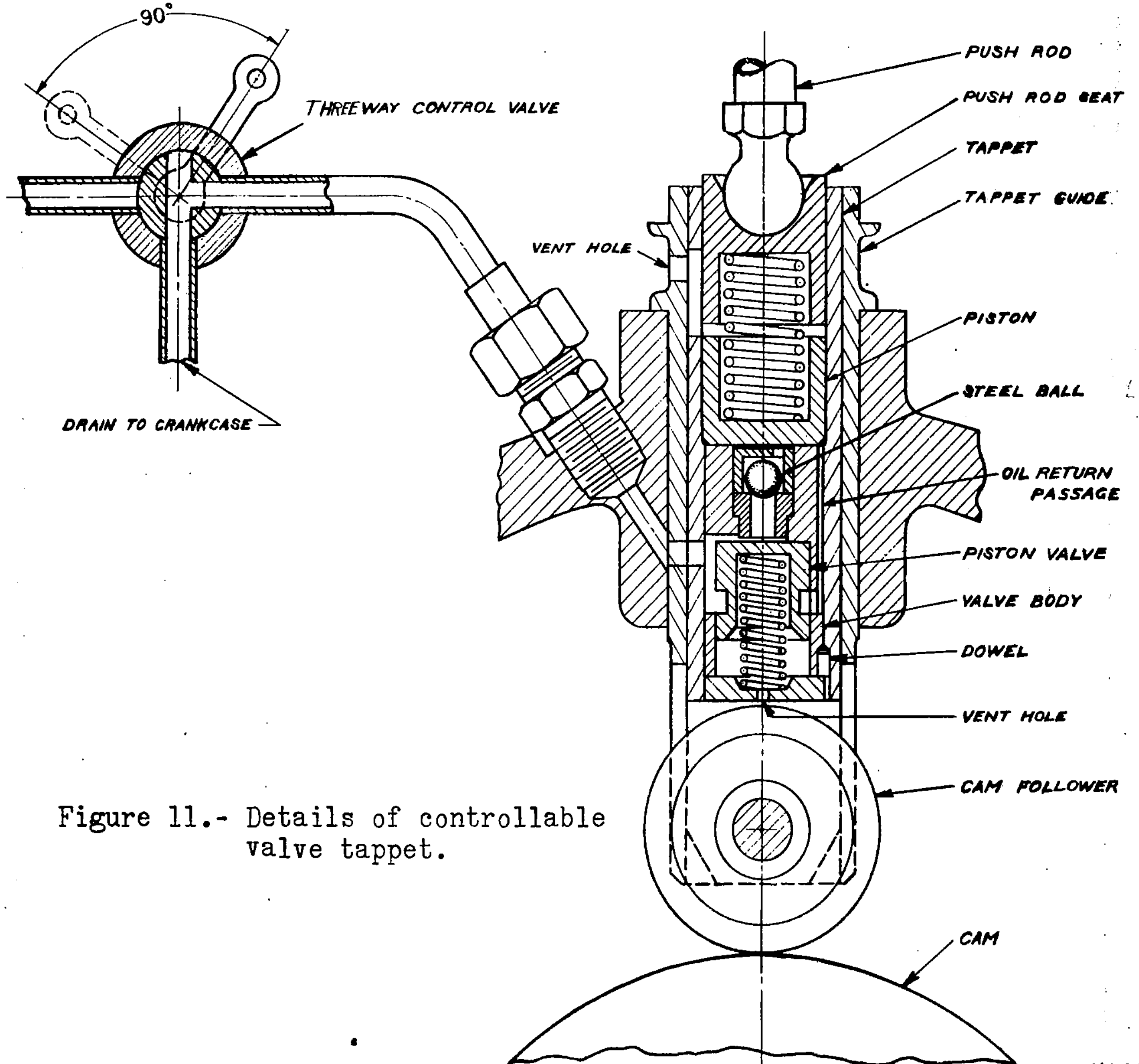


Figure 11.- Details of controllable valve tappet.

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